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Publication date	2017-05-18
Original Citation	Fernandez, C., Pavlović, Z., Kulkarni, S., McCloskey, P. and O'Mathúna, C. (2017) 'High frequency, single/dual phases, large AC/DC signal power characterization for two phase on-silicon coupled inductors', 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, USA, 26-30 March. doi:10.1109/APEC.2017.7931048
Type of publication	Conference item
Link to publisher's version	10.1109/APEC.2017.7931048
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High Frequency, Single/Dual phases, Large AC/DC signal power characterization for two phase on-silicon coupled inductors

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***Abstract*— In this work, a new set-up is presented to characterize the large signal electrical parameters of on-Silicon integrated coupled inductors for Power Supply on Chip. The proposed system is suitable to perform the measurements under different large-signal test conditions given by the dc bias current up to 2 A and ac current through one or both windings, with amplitudes ranging from 0 A to 0.5 A at frequencies up to 120 MHz. Since a key issue when measuring at high-frequencies is the error due to the attenuation and time skew between the channels, an additional test is performed to characterize the measurement system and compensate the voltage and current waveforms.**

Keywords—impedance measurement, integrated magnetics, thinfilm inductors, large signal testing

I. INTRODUCTION

The trend towards miniaturization and integration of power management unit in microelectronics imposes the need for high-efficiency, high-performance power delivery. Multi-functionality of today's electronic devices requires generation of different power rails increasing granularity level of voltage regulators (VR). By bringing VR in close proximity to the load the efficiency losses due to parasitic interconnections can be minimized. This would require co-integration of active switches and passive components on the same chip. Another advantage of VR integration is its ability to address the challenge from the load for fast dynamic response. This becomes more interesting as dynamic voltage scaling is needed in microcontrollers and multicore processors to enable energy efficient operation [1-2].

A buck type dc-dc converter is the most commonly employed topology choice for Integrated VR (IVR), since it offers higher efficiency compared to linear and hybrid regulators and performs step down function as required by the applications. The realization of a low loss inductor is a key challenge for the successful development of a power supply on chip solution. It can be designed either with or without magnetic core material. Air core inductors do not suffer from core losses but require higher converter switching frequency operation due to the relatively low inductance value [3, 4]. In order to obtain adequate inductance densities at lower switching frequencies, the integration of magnetic material is required. Considerable effort has been made recently to design and construct suitable magnetic core for inductors to be used in IVR applications, [5-9]. However, there is a trade-off between high efficiency and fast transient response in buck converters using uncoupled inductors. Phase interleaving is used to improve transient response, improve light load efficiency and reduce output current ripple. This is addressed through use of silicon inductors with negatively coupled phases, which uses the leakage inductance for storing energy and hence can provide rapid transient response. Additionally, the negatively coupled phases reduce the output ripple through reduced summation of currents in different phases, while turning on/off of phases can improve light load efficiencies.

Increasingly, researchers have focused on developing new magnetic thin films and device constructions, to address the need for realizing on-silicon coupled inductors, capable of operating at very high frequencies up to 200MHz. This highlights the challenge of characterizing these materials and devices at these high frequencies. Characterization at high frequencies using network analyzers are widely used, but they can only apply a small signal current, thereby only providing information of copper and core eddy current losses. A large signal characterization set-up is required to accurately measure the loss performance of coupled inductor device before a full VR test.

The large signal characterization conditions are typically selected to match those of the actual converter, so the device impedance measurement gives information of total core loss including eddy current, hysteresis and anomalous losses. The key issues of the large-signal measurement system are both the generation of the adequate excitation signal as well as a high-precision to measure the equivalent impedance. There have been significant number of reports on large signal characterization of discrete passive devices. However, the reports on integrated thin film devices have been limited, particularly due to the need for higher frequency characterization [6-16]. This work presents the large signal tests performed to characterize a device up to 100 MHz, comparing the proposed set-up with the one already presented in a previous work, which allowed measurements till 15 MHz.

II. ON-SILICON COUPLED INDUCTOR DEVICES

This paper describes a new large signal characterization system for on-silicon coupled inductors at very high frequencies (40-120MHz). The validation of the test methodology is done using two-phase coupled inductors micro-fabricated on silicon. The device specifications for the on-silicon coupled inductor are given in Table 1.

Further, the fabricated device structure is shown in Fig. 1, and is formed by two coupled equal coils with self-inductance equal to 47 nH and with coupling factor of less than 0.4. The design, fabrication and small signal characterization of this device is reported in previous publications [17, 18]. Further, the first revision of a large signal characterization set-up has been reported previously in [18], but the described approach has limitations when used for large signal characterization for frequencies beyond 15 MHz.

TABLE 1 CHARACTERISTICS OF THE COUPLED INDUCTORS UNDER TEST

Inductance	47 nH
Coupling coefficient	0.4
Core thickness	1.6 µm
Core length	1.78 mm
Copper width	50.62 µm
Copper thickness	15 µm
DCR	0.3425 Ω
Device footprint	2 mm^2

Fig. 1 Micro-fabricated two phase coupled inductor

III. PRECISE LARGE SIGNAL MEASUREMENT AT HIGH FREQUENCY

The typical approach to large signal characterization of the on-silicon coupled inductors is done through applying the appropriate excitation either in one or two phases and measuring voltage and current in order to calculate the impedances. The challenge is the accurate extraction of the voltage and current waveforms at higher frequencies. A key issue with the previous approach was that the impedance of device matched the impedance of the oscilloscope, hence providing an alternate path for the current.

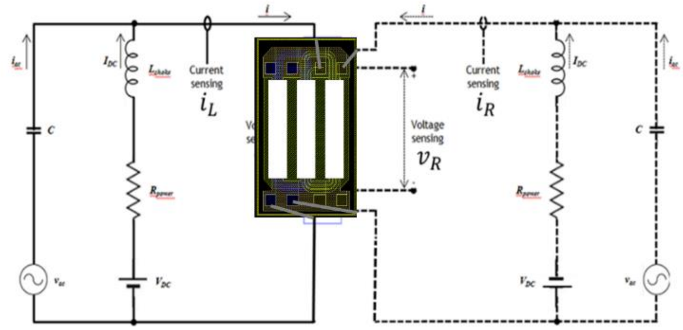


Fig. 2 Schematic of the large signal testing circuit

A new experimental set-up has been designed in order to: 1) set the conditions similar as possible to those that device would have on the actual converter; 2) improve the accuracy of the measurements till higher frequencies. This set-up allows applying dc bias current up to 2 A and ac current through both windings up to 120 MHz. The circuit is divided into three blocks: the signal generation system, the measurement system and the compensating system. As shown in the schematic in Fig. 2 (not including the compensation system), the excitation signals for each winding are generated by two different branches connected in parallel:

- A 50 Ω output resistance RF-amplifier model 25A250A from Applied Research, controlled by a signal generator model Agilent E8257D, injects the ac current to the PCB circuit through an SMA connector. The RF Amplifier is series-connected to a decoupling bank capacitor composed of 2 SMD 100 nF 25 V devices.

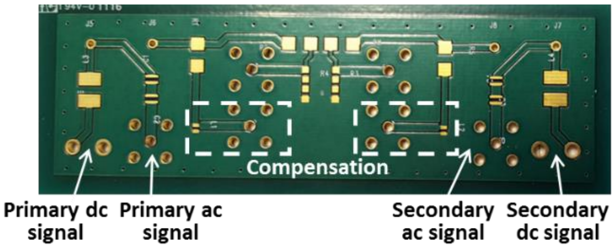
- The dc current is generated by a dc source connected in series with an inductance SMD 1812 3.3 µH from Wurth Elektronics in order to block the ac current and a 10 Ω power resistor to limit the total current.

The main sources of errors in the measurements are:

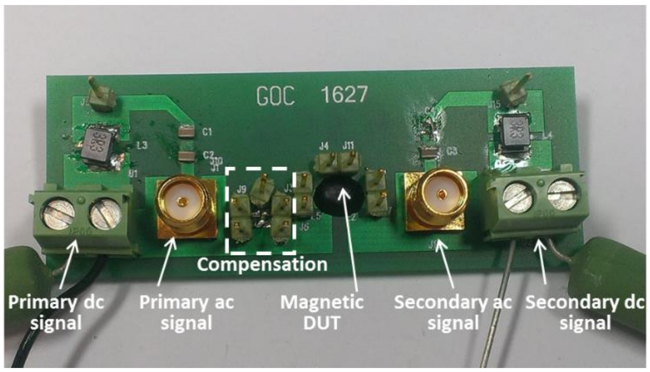
- Noise, which has been minimized by a proper routing of the board. Two printed circuit boards were designed, shown in Fig. 3. The improved design (Fig. 3.b) includes a ground plane, the 4-wire measurement and small current loops to the connectors where the oscilloscope probes are connected.

- Error in amplitude measurement. Low tolerance components are used in the testing board, but since the impedance is measured directly from the voltage and current waveforms, the only source of error are the probes themselves. The current monitors exhibit amplitude response as a function of the frequency and so the current waveform can be attenuated. This attenuation should be measured and taken into account during the post-processing of the waveforms.

- Delay between the signals. Voltage and current probes have their own characteristic propagation delay, so the current and voltage waveforms measured by the scope can be time-skewed relative to each other. This means that the data pairs are not time coincident, and thus it is mandatory to provide a way to correct the time-skew during the post-processing of the waveforms.



a) First large signal set-up



b) Improved large signal set-up

Fig. 3 Large signal testing circuit

In this set-up, voltage and current have been measured using the following probes:

- Voltage probes: two different voltage probes have been tested, as explained in next section. Voltage measurements in the terminals of the magnetic device have been taken by using a 4-terminal Kelvin connection, being the driven current traces separated to the voltage measurement traces. Two different boards, depicted in Fig. 3, were designed due to the two different voltage probes.
- Current probes: the Pearson Current Monitor model 2877 is selected for the current measurements. This 200 MHz bandwidth probe inserts a low delay compared to the alternative current probes. According to the data sheet, this phase-shift if about 6º at 20 MHz (equivalent to 0.8 ns). However, it is only suitable for ac current and saturates at moderate values of dc bias. To avoid this saturation, the dc current has been compensated through the current monitors.

The first step in the large signal test is to determine the attenuation due to the measurement system, as well as the time delay between channels. This test is performed measuring the voltage across and the current through a capacitor whose impedance is known at the frequency of the test (compensation blocks in Fig. 3). The voltage and current waveforms are compared to the theoretical ones in order to calculate the attenuation and delays introduced by the probes and the measurement system. These values are taken into account off-line. Therefore it is required to post-process the voltage and current waveforms to compensate the attenuation and to de-skew.

The designed set-up permits testing with dc and ac current through one or two windings. Depending on the measured voltage and current, the self-impedance or the mutual impedance can be identified in different working conditions.

IV. Large Signal Coupled Inductor Measurements & Discussion

The measurement methodology described in the previous section has been applied for characterizing the described two phase on-silicon coupled inductor.

A SMD capacitor with a 220nF capacitance was used to characterize the current monitor. The Q-factor of the capacitor was used to estimate the current lag and current attenuation at different frequencies. Fig. 4 shows the voltage and current waveforms measured from this test, performed at 60 MHz. The first harmonic of the measured voltage and current was calculated and the attenuation and delay calculated comparing with the expected theoretical current waveform, also shown in the figure.

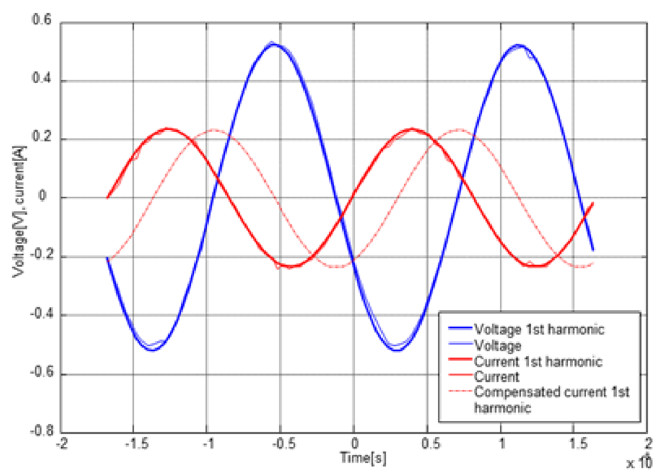


Fig. 4 Current and Voltage waveforms from SMD capacitor measurement to identify lag and attenuation

A. *Comparison between the voltage probes*

The data on impact of different probes is shown in Table 2 where the test condition was applying current in phase 1 of the coupled inductor and measuring voltage across phase 2. Here the inductance measured is the magnetizing inductance. From the table it is clear that while the impact on inductance calculation is limited with the different probes, the real variation is seen in the resistance measurement. As can be seen, the resistance measured with the higher impedance probes show a decrease in value from 40 MHz to 80 MHz, which is not consistent with theory, whereas the lower impedance probes show a more consistent result with the resistance at 80 MHz increasing by almost 2 times the value at 40MHz.

TABLE 2 MEASURED IMPEDANCES USING VOLTAGE PROBES WITH DIFFERENT IMPEDANCE

Voltage probe	Frequency (MHz)	Idc (A)	Iac (mA)	Magnetizing inductance (nH)	Core resistance (Ω)
11 pF	40	0	24	14.64	1223
1 pF	40	0	20	14.96	609
11 pF	80	0	25	16.72	987
1 pF	80	0	50	16.63	1171

At higher test frequencies the impedance of the probes could introduce additional path for currents and hence, there is a need to use lower impedance probes for improved accuracy. This is the reason why a second large signal set-up was designed (Fig. 3.b), including new connectors for the low impedance probes Tektronix TAP1500 (Fig. 5). The voltage measurements in the terminals of the transformer have been taken by using a 4-terminal Kelvin connection, being the driven current traces separated to the voltage measurement traces. Due to the size of the connectors, in this set-up the current loop of the voltage probes is minimum.

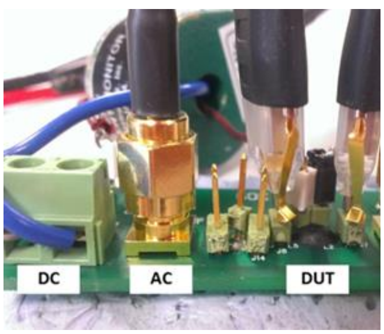


Fig. 5 Large signal test board with the low impedance voltage probes

B. *Large-signal tests with the improved set-up*

In this section the large signal test performed using the improved set-up with the low impedance probes are shown.

A first test was done producing only ac current through the primary winding at different frequencies, from 20 MHz to 100 MHz, and with an amplitude equal to 30 mA. As shown in Fig. 6 the inductance is not very sensitive to this variation. This measurement is consistent with the small-signal measurements.

Some preliminary large signal tests were done producing dc current through the primary winding as well as ac current through the primary winding. These tests were done at two different frequencies 80MHz and 100 MHz with varying ac and dc currents. At each frequency the large signal testing was done at two different ac currents (100mA and 200mA). Additionally, these tests were repeated for different dc currents (0-1 A).

Fig. 7 and Fig. 8 show the measured inductance at 80MHz and 100 MHz respectively. From the figure it is clear that increasing ac current amplitude from 100 mA to 200 mA does not have a strong impact on the inductance. On the other hand, inductance decreases with applied dc bias current. This is consistent with theory, that as the core is excited with a field close to saturation field, the relative permeability is lower and hence resulting in lower inductance. On the other hand, the saturation current level defined as the current where a 20% drop in the inductance value occurs is 750mA.

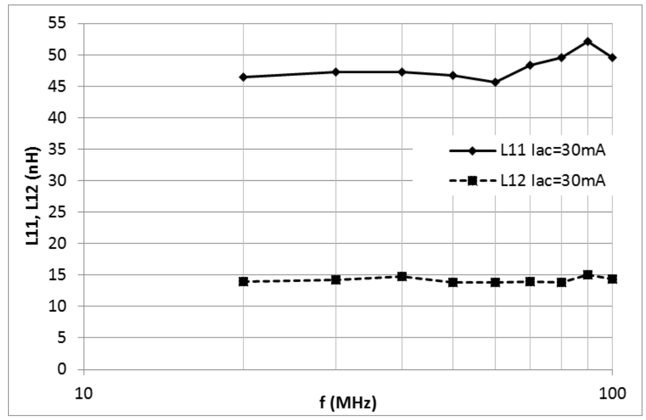


Fig. 6 Inductance measured at different frequencies (ac current through primary winding)

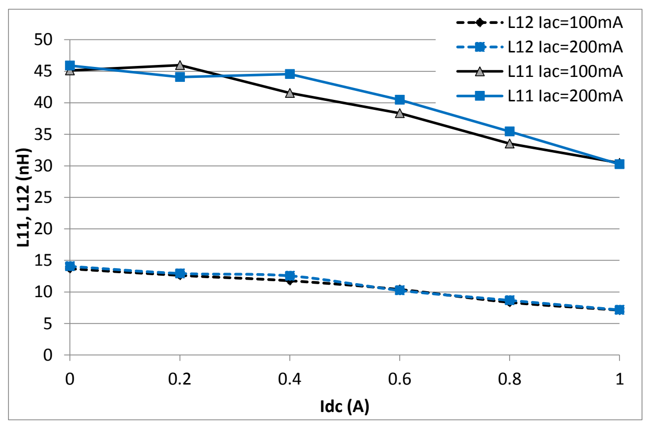


Fig. 7 Inductance measured at different ac and dc currents at 80MHz (dc and ac current through primary winding)

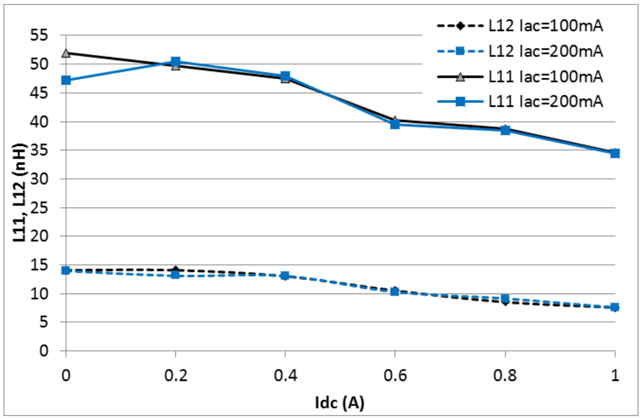


Fig. 8 Inductance measured at different ac and dc currents at 100MHz (dc and ac current through primary winding)

Additionally, a comparison among the measured core resistance R_{12} is shown in Table 3. Since eddy currents are proportional to the square of frequency, so the losses increase as the frequency increases.

TABLE 3 COMPARISON OF THE MEASURED CORE RESISTANCE IN DIFFERENT LARGE SIGNAL TESTS WITH 0 DC CURRENT

Frequency (MHz)	Core resistance (Ω)
80	2624
100	3739
120	6760

Further large signal tests were done producing dc current through both windings and ac current only through the primary winding. These tests were done at two different frequencies 100MHz and 120 MHz with two different amplitudes of the ac current (100mA and 200mA) and dc currents variable from 0 to 1 A.

The measured inductance is consistent with the previous measurements. On one hand, the measurements at null dc current are almost the same. On the other hand, in the previous test the measured saturation current level was 750 mA, while in this test a 20% drop in the inductance value occurs at approximately 1.3 A, being the magnetic coupling 0.4.

V. CONCLUSIONS

This work describes a large signal power measurement system and methodology for very high frequency (up to 120MHz). The paper explains the requirement of ideal voltage and current probes for accurate extraction of inductance and resistance of the device. The work also focuses on large signal measurement with both ac and dc signals in two phases of a coupled inductor to bring the testing condition close to real circuit performance.

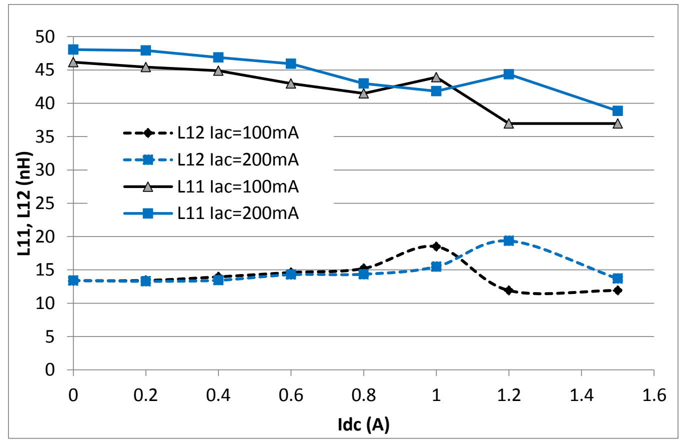


Fig. 9 Inductance measured at different ac and dc currents at 100MHz (ac current through primary winding and dc current through primary and secondary windings)

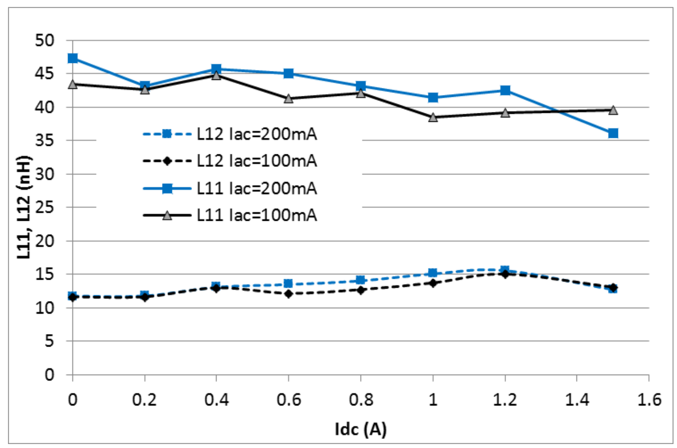


Fig. 10 Inductance measured at different ac and dc currents at 120MHz (ac current through primary winding and dc current through primary and secondary windings)

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